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MARS ORBIT RENDEZVOUS STRATEGY FOR THE MARS 2003/2005 SAMPLE RETURN MISSION[*]

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The baseline scenario for the Mars 2003/2005 Sample Return Mission utilizes Mars orbit rendezvous to retrieve two orbiting sample canisters containing Martian surface material. The two canisters, placed into Mars orbit by Mars ascent vehicles carried on landers launched in 2003 and 2005, will be retrieved by an orbiter launched in 2005 and returned to Earth in 2008. Rendezvous operations last for approximately one year and are divided into three phases: the preliminary (search and orbit determination) phase, the intermediate (orbit matching) phase, and the terminal (proximity operations and capture) phase. The focus of this paper is on the intermediate rendezvous phase. During intermediate rendezvous, nodal phasing orbits are used to significantly reduce the ΔV required to align the orbit planes of the orbiter and the sample canister. Preliminary analyses have shown that the total ΔV required for intermediate rendezvous (to retrieve two sample canisters) is approximately 478 m/s (99% probability). Two rendezvous test cases have been performed to validate the rendezvous strategy and associated maneuver profile and to confirm estimated ΔV requirements.

INTRODUCTION

The proposed Mars 2003/2005 Sample Return Mission will attempt to return to Earth two sample canisters containing a variety of samples of both Martian rocks and surface material. According to the current mission baseline, two Earth Entry Vehicles (EEVs), each containing one of the sample canisters, will be returned to Earth in October 2008, targeted to a northern hemisphere landing site. One candidate landing site is the U. S. Air Force Utah Test and Training Range (UTTR). In order to accomplish this first return of Martian samples to Earth, the Mars Sample Return (MSR) Mission will utilize numerous flight elements, including four launch vehicles (one Ariane-5, one intermediate-class launch vehicle, and two Mars Ascent Vehicles), two Martian landers, two Martian surface rovers, an orbiter, two orbiting sample (OS) canisters, and two EEVs. The MSR Mission is a cooperative endeavor between NASA and the French National Space Agency (CNES). CNES will provide the Ariane-5 and the orbiter.

The mission begins in May/June 2003 with launch of the NASA-provided 2003 lander, carrying a

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rover and a Mars Ascent Vehicle (MAV), on an intermediate-class launch vehicle. The 2003 lander will arrive at Mars in December 2003/January 2004. The lander will deploy the rover to collect samples of rocks and surface material from several different sites, and additional samples will be collected with a drill mounted on the lander. The samples collected by the rover and the lander (total of 500 grams) are transferred to a sample canister that is inside the MAV. The MAV is launched into low Mars orbit, targeted for a 600 km circular altitude orbit with a 45 deg inclination, and releases the OS to await retrieval by the orbiter. The OS is a small (14-16 cm diameter) spherical object which contains a radio beacon powered by solar cells and which has no attitude or trajectory control capability. The maximum duration of Mars surface operations is approximately 90 Martian days, or sols (90 sols = 92.5 Earth days), which is the design lifetime of the lander. Thus the 2003 MAV will be launched no later than April 2004.

In August 2005, a second virtually identical NASA-provided lander, carrying a duplicate rover and MAV, and a CNES-provided orbiter will be launched together on an Ariane-5 (also provided by CNES). Both the lander and the orbiter arrive at Mars in July/August 2006. A second OS is delivered to low Mars orbit using the same scenario as was used for the 2003 lander mission. The orbiter uses aerocapture and several small orbit trim maneuvers for insertion into the baseline post-MOI (Mars Orbit Insertion) orbit which has a periapse altitude[1] of 250 km, an apoapsis altitude of 1400 km, and an inclination of 45 deg. During the orbiter's approximately one-year stay at Mars, it will search for and rendezvous first with the 2003 OS and then with the 2005 OS. After retrieval, each OS is transferred to an EEV. The orbiter departs Mars in July 2007 and returns to Earth in October 2008 on a trajectory targeted to the desired landing site. After deploying the two EEVs, the orbiter will perform a deflection maneuver to avoid entry into Earth's atmosphere. A more detailed description of the overall Mars 2003/2005 Sample Return Mission is given in Reference 1.

Mars orbit rendezvous is a key component in the architecture of the MSR Mission. The Mars orbit rendezvous strategy described in this paper is similar to the lunar orbit rendezvous strategy used for the Apollo missions and the Earth orbit rendezvous strategy used for Shuttle rendezvous operations. One significant difference for the Mars orbit rendezvous scenario is that the final phase of rendezvous leading to capture of the OS by the orbiter must be accomplished by a fully autonomous onboard rendezvous system. The primary reason for this is that the necessity for rapid response during the final phase of rendezvous precludes using a ground-based system, because the round-trip light time between Earth and Mars ranges from 23 minutes to 43 minutes during the Mars orbit rendezvous time period. Another significant characteristic that distinguishes the Mars orbit rendezvous scenario is that nodal phasing orbits (explained in the next section) are used to align the orbit planes of the orbiter and the OS in order to significantly reduce the total ΔV required for rendezvous.

The remainder of this paper addresses the following topics: overview of Mars orbit rendezvous, Mars orbit rendezvous strategy and maneuver analysis results, rendezvous test cases, future work, potential benefits of a priori knowledge of the 2003 OS orbit, and summary and conclusions.

MARS ORBIT RENDEZVOUS OVERVIEW

Rendezvous Phases

Mars orbit rendezvous (for each OS) has been divided into three phases: preliminary rendezvous, intermediate rendezvous, and terminal rendezvous. The key characteristics of each phase are shown in Table 1, and the current baseline MSR rendezvous timeline is shown in Figure 1. There are two main goals of the preliminary rendezvous phase. The first goal is to search for and detect the OS using the orbiter's Radio Direction Finder (RDF) to listen for a solar-powered beacon signal (401.5 mHz) transmitted from the OS. The effective range of the RDF is 3000 km, and the RDF provides data only when the OS is in sunlight and not occulted by Mars as seen from the orbiter. The second goal is to accurately determine the orbit of the OS using RDF data downlinked to Earth. The RDF outputs are two angles that determine the direction from the orbiter to the OS. (The RDF system can also determine the range to the OS, but only at ranges less than approximately 100 meters.). It may also be possible to use the OS beacon signal to acquire 1-way or 2-way Doppler data from non-MSR flight elements, such as the European Space Agency (ESA) Mars

[1] The Mars mean equatorial radius is 3393.4 km.

Express orbiter (scheduled to be launched in 2003), the NASA Mars Surveyor 2001 orbiter, or the proposed Mars 2003 navigation and communications orbiter. (To reduce power and onboard processing requirements for the MSR orbiter, the current mission plan does not include acquisition of Doppler data from the OS.) During the preliminary rendezvous phase, traditional ground-based navigation is used to determine the orbits of the orbiter and the OS, and any propulsive maneuvers for trajectory control are computed on the ground and uplinked to the orbiter.

Table 1

RENDEZVOUS PHASES

Phase	Start	End	Primary Sensor (Backup/ Enhancement)	Strategy
Preliminary (Search and OD)	2003: After MOI phase 2005: After MAV launch	2003: Start of nodal phasing 2005: At 2003 rendezvous	RDF (Mars Express or Mars 2001 2-way Doppler)	Ground-based navigation; detect RDF signal from sample canister and determine orbit with angular data from RDF system
Intermediate (Orbit Matching)	2003: Start of nodal phasing 2005: After 2003 rendezvous	Transition to terminal rendezvous phase (end of Hohmann transfer)*	RDF (Mars Express or Mars 2001 2-way Doppler)	Ground-based navigation; perform orbit determination with angular data from RDF; execute series of 8-10 maneuvers to accomplish nodal alignment and (nearly) match orbits with sample canister
Terminal (Proximity Operations & Capture)	Transition to terminal rendezvous phase (end of Hohmann transfer)*	Sample capture	LIDAR (duplicate LIDAR, RDF angles only, RDF angles and range)	Autonomous, onboard rendezvous system; LIDAR range and angular data used for relative state estimation; closed-loop, guided approach using sequence of many small maneuvers; standoff point at 80-m separation distance

*For example: 0.5 km below and 200 km behind the OS in a co-elliptic orbit.

MOI = Mars Orbit Insertion RDF = Radio Direction Finder

MAV = Mars Ascent Vehicle LIDAR = Light Detection and Ranging System

For the 2003 OS, the preliminary rendezvous phase starts after the Mars orbit insertion (MOI) phase for the orbiter is completed and ends at the start of the 2003 OS nodal phasing period. The orbiter arrives at Mars in July/August 2006; the exact arrival date depends on the actual Earth launch date. The 2003 OS will have been placed in orbit by the 2003 MAV more than two years earlier, nominally in March 2004. For the 2005 OS, the preliminary rendezvous phase starts after the 2005 MAV launch (which will take place sometime within 90 sols of MOI) and ends when the 2003 OS has been retrieved. The preliminary rendezvous phase for the 2005 OS will almost certainly occur concurrently with 2003 OS rendezvous operations, primarily during the 2003 OS nodal phasing period. During 2003 OS rendezvous operations, the orbiter will have to periodically devote time for acquisition of RDF data from the 2005 OS in order to maintain knowledge of its orbit at an acceptable accuracy level. During the preliminary rendezvous phase, non-MSR flight elements may allow acquisition of OS-orbiter Doppler data to use in addition to RDF data for OS orbit determination.

During the intermediate rendezvous phase, the orbiter performs a series of 8-10 propulsive maneuvers to change the orbit inclination, node, semi-major axis, eccentricity, and line of apsides of the orbiter to nearly match those of the OS. The goal is to deliver the orbiter to an orbit that is co-elliptic with that of the OS (same inclination, node, eccentricity, and line of apsides) but with a slightly smaller semi-major axis and with the orbiter below and behind the OS. This will ensure that at the start of the terminal rendezvous phase, the orbiter will be closing on the OS, but in a slightly lower orbit so as to eliminate any possibility of collision. The exact difference in semi-major axis and the distance that the orbiter is behind the OS have not been determined; these parameters depend on navigation delivery accuracy and the baseline scenario selected for the terminal rendezvous phase. In any case, these parameters will be chosen such that it will take several days for the orbiter to pass below the OS if no further action were taken. For the 2003 OS, the intermediate rendezvous phase starts at the beginning of the nodal phasing period and ends at delivery to the terminal rendezvous transition point. The terminal rendezvous transition point is defined to be at the completion of the final maneuver of the Hohmann transfer that occurs at the end of the intermediate rendezvous phase. For the 2005 OS, the intermediate rendezvous phase starts after the 2003 OS has been retrieved and ends at delivery to the terminal rendezvous transition point. During the intermediate rendezvous phase, ground-based navigation is used for orbit determination and maneuver calculations using angular data from the RDF system to determine the OS orbit. As was the case for the preliminary rendezvous phase, non-MSR flight elements may allow acquisition of OS-orbiter Doppler data to use in addition to RDF data for OS orbit determination.

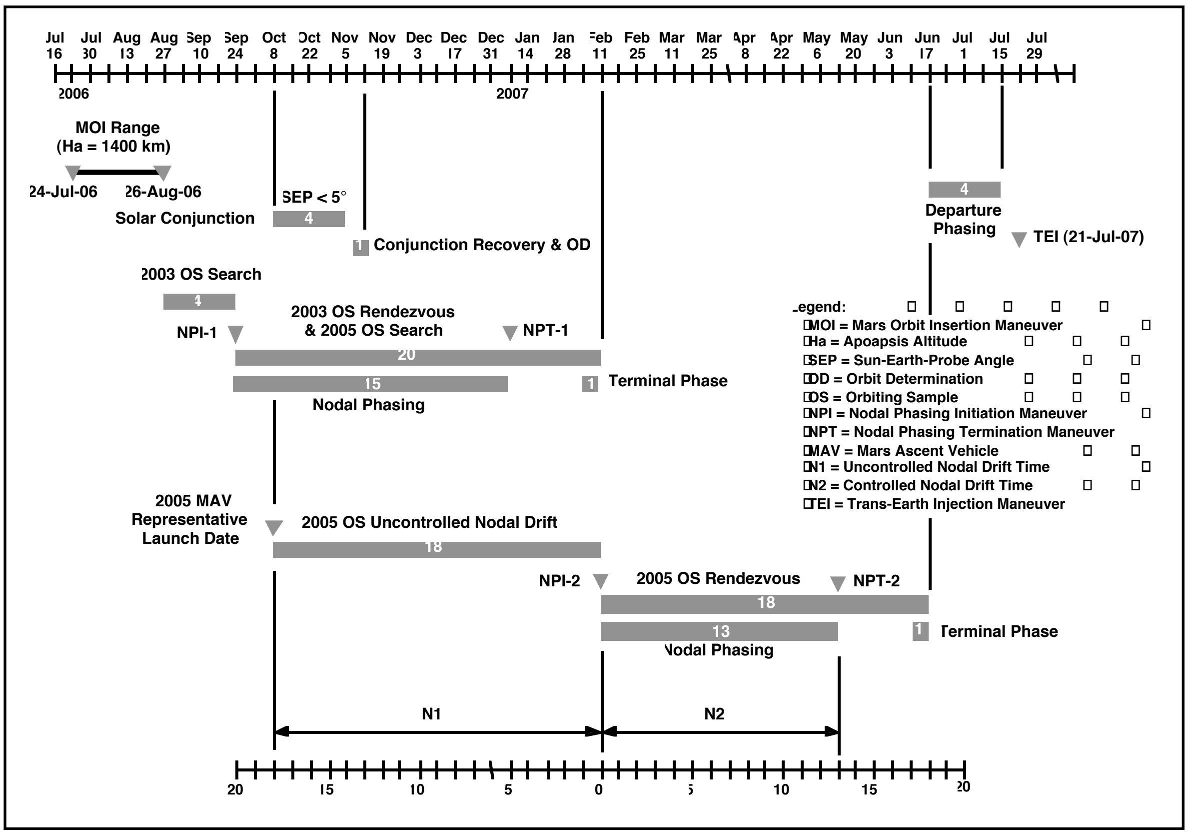

Figure 1 Mars Sample Return Rendezvous Timeline

In order to significantly reduce the ΔV required for the orbit-change maneuvers during the intermediate rendezvous phase, nodal phasing orbits are used to align the orbit planes of the orbiter and the OS. Because there can be large nodal differences between the orbiter and the OS, the ΔV to align the nodes using propulsive maneuvers would be prohibitive. Non-spherical Mars gravity field harmonics (primarily J_2) cause the node to regress. The nodal regression rate decreases with increasing semi-major axis (i.e., proportional to $1/a^{3.5}$). By changing the semi-major axis of the orbiter to establish a differential nodal drift rate between the orbiter and the OS, the node of the orbiter will match that of the OS after a specified amount of time. For the current baseline rendezvous timeline (Figure 1), the intermediate rendezvous phase lasts 19 weeks for the 2003 OS and 17 weeks for the 2005 OS. As Figure 1 indicates, the majority of the time during the intermediate rendezvous phase is spent with the orbiter in a nodal phasing orbit.

The terminal rendezvous phase starts at delivery of the orbiter to the terminal rendezvous transition point mentioned above and ends with capture of the OS inside a capture basket onboard the orbiter. Terminal rendezvous operations are accomplished by an autonomous onboard rendezvous system to effect a closed-loop, guided approach to the OS using RDF angular data and data from a laser radar system, also referred to as LIDAR (light detection and ranging system). The LIDAR provides both range and direction to the OS when the OS is within approximately 5 km of the orbiter. The LIDAR is the primary sensor for determining the position of the OS with respect to the orbiter when the OS is within the effective range of the LIDAR. When the OS is beyond 5 km, the RDF is the primary sensor. The RDF can also serve as backup to the LIDAR (providing range in addition to angular data) when the range to the OS is within approximately 100 meters. Terminal rendezvous scenarios and simulation results are described in more detail in an accompanying paper (Reference 2). In the current baseline rendezvous timeline, one week is allocated for the terminal rendezvous phase for each OS.

The focus of this paper is the strategy to accomplish the intermediate phase of Mars orbit rendezvous with the goal of minimizing the total ΔV required for orbiter propulsive maneuvers. The strategy described in this paper may be considered to be a point design and is expected to change as a better understanding of the Mars orbit rendezvous problem is gained.

Time Constraints, MAV Dispersions, and Nodal Phasing Orbits

This section contains a discussion of certain key factors that have a significant effect on the development of the baseline Mars orbit rendezvous strategy and on the total ΔV required to accomplish rendezvous with the 2003 OS and the 2005 OS. These factors include rendezvous time constraints, the effects of MAV orbit injection errors, and the use of nodal phasing orbits.

One important factor is the time available for intermediate rendezvous. As indicated on the rendezvous timeline (Figure 1), the orbiter will arrive at Mars sometime between 24 July and 26 August 2006 (depending on Earth launch date). Departure from Mars, also referred to as Trans Earth Injection (TEI), is planned to occur on 21 July 2007. This TEI date minimizes the departure energy for the Mars-Earth return trajectory and also corresponds to a near-minimum approach speed at Earth. Taking into account the time allocated for the 2003 OS search, terminal rendezvous, and departure orbit phasing, this leaves (for the worst case latest Mars arrival date) a total of 36 weeks to accomplish the intermediate rendezvous phase for the 2003 OS and the 2005 OS. The 36 weeks may seem like a long time, but it is actually an important constraint for the nodal phasing strategy and the ΔV required for intermediate rendezvous (as explained below).

MAV orbit injection errors are another important factor. The design of the MAV is being driven by strict mass and cost constraints. The MAV will be a simple, lightweight, 2- or 3-stage, solid-fueled launch vehicle with limited guidance capabilities. Cost constraints dictate the use of an Inertial Measurement Unit (IMU) which is also a low-cost, lightweight unit that does not have high accuracy. As a result, preliminary MAV six-degree of freedom trajectory simulations indicate that MAV orbit injection errors can cause significant OS orbit dispersions. In order to limit these dispersions, the design of the MAV must meet the following requirements (relative to the 600 km altitude circular, 45 deg inclination target orbit): ±100 km (3σ) for semi-major axis, ±1.0 deg (3σ) for inclination, and ±3 deg (3σ) for node. The requirement for node is fairly loose, because nodal errors of several degrees can easily be accommodated during the nodal phasing process described below. For the results presented in this paper, the eccentricity of the OS orbit was assumed to be no larger than 0.037 (3σ).

These OS orbit dispersions have significant effects on rendezvous ΔV, both directly and indirectly. An example of the direct effect is that the ΔV required to change the orbiter's inclination by one degree is about 60 m/s. Another example of the direct effect is that the ΔV required to raise or lower the orbiter's semi-major axis by 100 km is about 40 m/s.

The OS orbit dispersions cause a significant indirect ΔV cost as well. The 2003 OS will be placed in orbit by the 2003 MAV no later than April 2004, according to the current mission plan. Thus, the 2003 OS will be in orbit for over two years before the 2005 orbiter arrives at Mars in July/August 2006 and commences to search for the 2003 OS by listening for its radio beacon signal. The nodal regression rate for the target OS orbit (600 km altitude circular at 45 deg inclination) is 6.09 deg/day. A semi-major axis dispersion of ±100 km (3σ) corresponds to a nodal regression rate dispersion of ±0.54 deg/day (3σ). Between April 2004 and July 2006, the uncertainty in the node of the 2003 OS will grow to about ±450 deg (3σ)[2]. This means that the location of the node of the 2003 OS, and consequently the nodal difference between the orbiter and the OS, can be anywhere between 0 deg and 360 deg with essentially equal probability. The ΔV cost to correct arbitrarily large nodal differences with out-of-plane maneuvers would be prohibitive. Instead, nodal phasing orbits are used. A maneuver is performed to change the semi-major axis of the orbiter to establish a differential nodal drift rate until the orbiter and OS nodes are aligned (which may take many weeks); then, another maneuver is performed to null the differential nodal drift rate. The ΔV to accomplish nodal alignment cannot be eliminated, but it can be reduced to a reasonable level by using nodal phasing orbits. The longer the time allowed for nodal phasing, the lower is the ΔV cost to align the orbiter and OS nodes for all possible initial orientations.

The same nodal alignment problem exists for the 2005 OS rendezvous. The 2005 MAV will place the 2005 OS in orbit sometime within 90 sols after arrival of the 2005 lander at Mars. The MAV launch time of the day will be chosen such that the orbit of the 2005 OS will have a specified node when the 2003 OS rendezvous is completed; this specified node is close to that predicted for the orbiter at completion of the 2003 OS rendezvous. (In some cases, the ΔV required for nodal phasing can be reduced by biasing the target node from that predicted for the orbiter at completion of the 2003 OS rendezvous.) However, once the MAV is launched, semi-major axis dispersions of the OS orbit will cause a nodal error to accumulate at a rate which is dispersed by about ±0.54 deg/day (3σ) from the nominal nodal drift rate. Only after the 2003 OS rendezvous is completed can the orbiter begin the nodal phasing process for the 2005 OS by changing semi-major axis. The variable N1 is used to denote the time period (number of weeks) during which the 2005 OS nodal error is accumulating due to an uncontrolled differential nodal drift rate. The variable N2 is used to denote the time period (number of weeks) the orbiter spends in the nodal phasing orbit with a controlled differential nodal drift rate. N1 and N2 are illustrated on Figure 1. The reference for measuring N1 and N2 is the time of completion of the 2003 OS rendezvous. The sum of N1 and N2 is a constant 31 weeks for the assumed 2005 MAV launch date of 8 October 2006 (just before solar conjunction). For the timeline shown in Figure 1, the maximum nodal error of the 2005 OS at completion of the 2003 OS rendezvous is approximately ±70 deg (3σ).

The Mars orbit rendezvous problem for the MSR Mission is the most general type of orbital rendezvous problem. It involves determining a series of maneuvers that will transfer a vehicle between non-circular, non-coplanar orbits (different semi-major axis, eccentricity, inclination, node, and line of apsides) in a non-spherical gravity field which causes secular changes to both the node and the line of apsides. The rendezvous strategy that is described in the next section has been developed to solve this problem.

Assumptions, Ground Rules, and Constraints

A listing of the key assumptions, ground rules, and constraints used in the development the Mars orbit rendezvous strategy is listed below. For dates mentioned below, refer to the rendezvous timeline shown in Figure 1.

High-Level Mission Guidelines.

- The rendezvous strategy must accomplish rendezvous with both the 2003 OS and the 2005 OS within the time period allocated for rendezvous operations (from 27 August 2006 through 17 June 2007).

- The following time periods are not available for the intermediate rendezvous phase: the first four weeks after MOI (search and orbit determination for the 2003 OS), the final four weeks before

[2] The nodal regression rate is also affected by inclination dispersions and non-zero eccentricity, but these are both second-order effects; the uncertainty in the location of the node is primarily caused by semi-major axis dispersions.

TEI (departure orbit phasing), and one week for the terminal rendezvous phase for each OS (following intermediate rendezvous).

• Propulsive maneuvers are prohibited during the solar conjunction period, defined as Sun-Earth-Probe (SEP) angle less than 5 deg, which lasts from about 8 October 2006 to about 5 November 2006; this period may be used for nodal phasing.

• The rendezvous strategy should be applicable for the entire range of Mars arrival dates for the orbiter corresponding to a 21-day launch period. The range of Mars arrival dates is from 24 July 2006 to 26 August 2006.

• The ΔV required for rendezvous should be decreased by trading time for ΔV where appropriate.

• The rendezvous strategy must not depend on support from non-MSR flight elements. In particular, no knowledge of the 2003 OS orbit is assumed prior to arrival of the 2005 orbiter at Mars.

Mars Orbit Insertion.

• Aerocapture and propulsive orbit trim maneuvers are used to achieve the baseline post-MOI orbit from which to start rendezvous operations.

• The target post-MOI orbit is 250 km (periapse altitude) x 1400 km (apoapse altitude) with an inclination of 45 deg. (The choice of the post-MOI orbit parameters is discussed in Reference 1.)

• The dispersions of the post-MOI orbit are ±250 km (3σ) for apoapsis altitude and ±0.5 (3σ) deg for inclination[3].

MAV Launch, Target Orbit, and Dispersions.

• The 2003 MAV will be targeted to achieve an OS orbit which is circular at an altitude of 600 km and an inclination of 45 deg.

• The 2005 MAV launch will be targeted to achieve an OS orbit which is circular at an altitude of 600 km and which has a specified inclination and node. The target <u>inclination</u> is equal to that predicted for the orbiter at completion of the 2003 OS rendezvous. The capability of targeting the 2005 MAV to the orbiter's inclination limits the inclination error that must be corrected for the 2005 OS rendezvous to ±1.0 deg (3σ). The target <u>node</u> (achieved by controlling the time of day of the MAV launch, given a target inclination and a particular launch site latitude) is that which will cause the 2005 OS to have a specified node when the 2003 OS rendezvous is completed; this specified node is close to that predicted for the orbiter at completion of the 2003 OS rendezvous. (In some cases, the ΔV required for nodal phasing can be reduced by biasing the target node from that predicted for the orbiter at completion of the 2003 OS rendezvous.)

• Launch of the 2005 MAV does not occur until after the orbit of the 2003 OS has been determined and the orbit of the orbiter at completion of the 2003 OS rendezvous has been predicted. This assumption is necessary to allow the 2005 MAV to be targeted to a specified inclination and node (see preceding paragraph).

• Launch of the 2005 MAV is assumed to occur on October 8, 2006. This is the latest launch date prior to the solar conjunction period that is consistent with the 90-sol design lifetime of the lander. This date is meant to be representative of the range of possible 2005 MAV launch dates.

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[3] The post-MOI apoapsis altitude dispersions have recently been reduced to ±100 km; the effect of this change on rendezvous ΔV is included in a later section of the paper.

• The OS orbit dispersions caused by MAV orbit injection errors are ±100 km (3σ) for semi-major axis, ±1.0 deg (3σ) for inclination, ±3 deg (3σ) for node, and eccentricity less than 0.037 (3σ).

Mars Departure.

• TEI occurs on July 21, 2007.

• The time allocated for departure orbit phasing prior to TEI is four weeks.

RENDEZVOUS STRATEGY AND MANEUVER ANALYSIS RESULTS

Rendezvous Strategy

The current baseline MSR Mars orbit rendezvous strategy is illustrated in Figure 2, which depicts, in a generic manner, the sequence of maneuvers and the various steps required to accomplish intermediate rendezvous. Note that the orbits in Figure 2 are not drawn to scale.

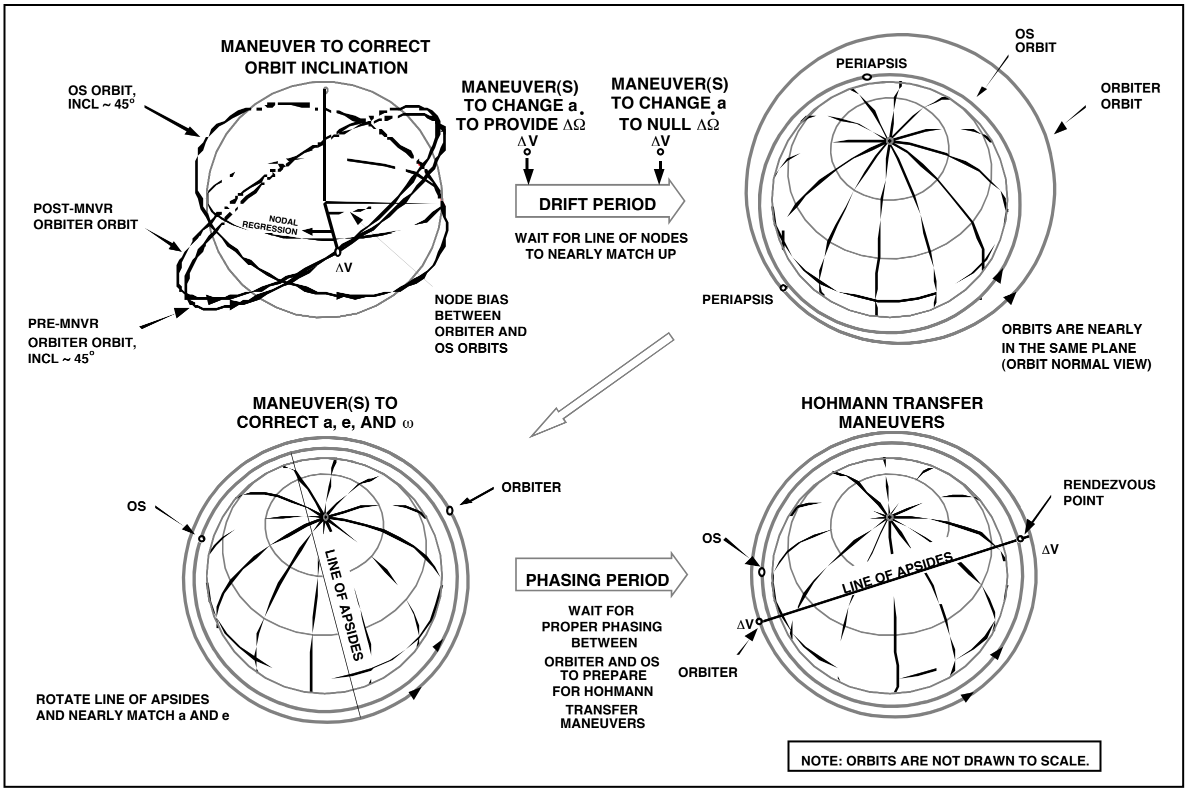

Figure 2 Mars Sample Return Intermediate Rendezvous Maneuver Scenario

At the start of the intermediate rendezvous phase, the OS will be in an orbit that is nominally a 600 km altitude circular orbit at an inclination of 45 deg, with dispersions within the bounds stated previously. The orbiter will be in an orbit that is significantly different from that of the OS, typically with substantial variations in semi-major axis, eccentricity, and the line of apsides. The inclination difference will be at most about 1.0 deg, but the nodal offset between the orbiter and the OS could be anywhere between 0 deg and 360 deg. The nodal drift rates of the orbiter and the OS will also, in general, be different due to the difference in semi-major axis. (Eccentricity and inclination differences have only second-order effects on the nodal drift rate.)

Inclination Correction. The first maneuver corrects the inclination of the orbiter to be the same as that of the OS. The ΔV cost to change inclination is approximately 60 m/s per degree of inclination change.

Nodal Phasing. After the inclination correction maneuver, a maneuver is performed to change the semi-major axis of the orbiter to establish a differential nodal drift rate with respect to the OS such that after a specified drift period, the nodes will be nearly aligned. (In some cases, two maneuvers may be optimal.) There are two options for establishing the differential nodal drift rate. In one case, the orbiter semi-major axis is <u>increased</u> to slow its nodal drift rate so that the OS will "overtake" the orbiter. For the other option, the orbiter semi-major axis is <u>decreased</u> to increase its nodal drift rate so that the orbiter will "overtake" the OS. The decision to increase or decrease semi-major axis is done to minimize the total ΔV required to accomplish rendezvous. The ΔV cost to change semi-major axis is approximately 40 m/s per 100 km of semi-major axis change. Each 100 km change in semi-major axis corresponds to a change in differential nodal drift rate of 0.54 deg/day.

After the nodes are nearly aligned, a maneuver is performed to change the semi-major axis of the orbiter to null the differential nodal drift rate. As was the case for the start of nodal phasing, in some cases, two maneuvers may be optimal. The minimum number of maneuvers required for the nodal phasing process is two – one to change semi-major axis at the start of nodal phasing and one to change semi-major axis at the end of nodal phasing. By using additional maneuvers, changes to the eccentricity and line of apsides of the orbiter can be combined with the semi-major axis changes to nearly match all three orbital elements with those of the OS, thereby reducing the total ΔV for intermediate rendezvous. The nodal phasing period lasts for many weeks and accounts for the majority of the time during the intermediate rendezvous phase.

Corrections for Semi-Major Axis, Eccentricity, and Line of Apsides. Following nodal phasing, several maneuvers are performed to correct the remaining differences in semi-major axis, eccentricity and line of apsides and to remove any small differences in inclination and node that may exist. After these maneuvers, the orbiter and OS will have the same inclination, node, eccentricity, and line of apsides, and almost the same semi-major axis.

In-Plane Phasing. After the maneuvers to correct semi-major axis, eccentricity, and line of apsides, it is necessary to leave a very small bias (<10 km) in the semi-major axis of the orbiter. The slight difference in orbital periods is used to bring the orbiter and the OS to the correct relative positions in their orbits so that the orbiter can then perform a near-Hohmann transfer to the terminal rendezvous transition point.

Hohmann Transfer. The final step of the intermediate rendezvous phase is to perform a near-Hohmann transfer to the terminal rendezvous transition point (nominally below and behind the OS). This requires two small maneuvers. After the Hohmann transfer, the terminal rendezvous phase is initiated to close on the OS and capture it. The scenario used for the terminal rendezvous phase is described in Reference 2.

2003 OS Maneuver Summary

For the 2003 OS rendezvous, the orbiter will start in the post-MOI orbit, which is 250 km (periapse altitude) x 1400 km (apoapse altitude) at a 45 deg inclination, with the following dispersions: ±250 km (3σ) apoapsis altitude and ±0.5 deg (3σ) inclination. The OS will be in an orbit that is nominally the target 2003 OS orbit, which is a 600 km altitude circular orbit at a 45 deg inclination, with the following dispersions: ±100 km (3σ) semi-major axis, ±1.0 deg (3σ) inclination, and eccentricity less than 0.037 (3σ).

The rendezvous timeline is shown in Figure 1. This timeline corresponds to the latest (worst case for rendezvous) Mars arrival date. The intermediate rendezvous maneuver sequence for the 2003 OS begins on 24 September 2006, after MOI and after the four-week OS search and OD phase is completed. The 2003 OS rendezvous is completed 20 weeks later on 11 February 2007 with capture of the OS by the orbiter. The intermediate rendezvous phase lasts for 19 weeks, of which 15 weeks are used for nodal phasing. The four-week time period after nodal phasing is used for the remaining orbit-matching maneuvers prior to the start of the terminal rendezvous phase.

Table 2 summarizes the intermediate rendezvous phase maneuvers for the 2003 OS rendezvous. For each maneuver, the table contains the purpose of the maneuver, comments that include the approximate time of the maneuver, and the ΔV statistics for the maneuver. It should be noted that the ΔV statistics quoted in the remainder of this paper are preliminary and are expected to change as a result of further analysis and changes to the intermediate rendezvous strategy. The maneuver sequence follows the rendezvous strategy outlined above. The nodal phasing termination (NPT) maneuver (Maneuver #3) is performed 15 weeks after the nodal phasing initiation (NPI) maneuver (Maneuver #2). The ΔV for the maneuvers to correct semi-major axis, eccentricity, and line of apsides so that they are almost identical to that of the OS is included in the line item for the nodal phasing maneuvers, because these corrections are optimally performed in conjunction with the nodal phasing maneuvers.

Table 2

2003 OS RENDEZVOUS MANEUVER SUMMARY

	Purpose of Maneuver	**Comments (See notes at bottom of table.)**	**ΔV (m/s)**		
			Mean	**1σ**	**99%**
1	Correct inclination of orbiter to be same as that of OS.	Performed after MOI phase is completed and orbit of OS is determined.	18	±14	60
2, 3	Maneuver #2 changes semi-major axis of orbiter to establish differential nodal drift rate with respect to OS. Maneuver #3 changes semi-major axis of orbiter to null differential nodal drift rate when nodes are nearly aligned.	Maneuver #2 performed a few days after Maneuver #1. Maneuver #3 performed 15 weeks later, when the line of nodes of orbiter and OS are within a few degrees of matching. (For some cases, three or more maneuvers may be required instead of just two.)	231	±22.5	300
4, 5	Correct a, e and ω of orbiter to be almost identical to that of OS: $\Delta a \cong 10$ km $\Delta e \cong 0$ $\Delta\omega = 0$ A small bias in a (and thus orbital period) is necessary such that the correct relative phasing will exist to allow rendezvous at Maneuver #8.	Maneuver #4 performed a few days after Maneuver #3. Maneuver #5 performed a few days after Maneuver #4. **The ΔV for these maneuvers is included in the total for Maneuvers #2 and #3.**	—	—	—
6	Correct errors in a, e, ω and i from previous maneuvers and alter the line of nodes, if necessary, to allow a co-planar relationship to exist at time of Maneuver #8 (rendezvous) with correct relative phasing.	Maneuver #6 performed about one week after Maneuver #5. (Under some circumstances two or more maneuvers may be required.)	12	±7	34
7	Initiate near-Hohmann transfer to desired transition point for start of terminal rendezvous phase.	Maneuver #7 performed about two weeks after Maneuver #6.	2.5	±0.7	4.5
8	Perform final maneuver for Hohmann transfer.	Maneuver #8 performed approximately one hour (one-half orbit) after Maneuver #7.	2.5	±0.7	4.5
		2003 OS Total	266	±27.5	349
Orbiter post-MOI orbit is 250 km x 1400 km, 45 deg inclination; apoapsis altitude ±250 km (3σ); inclination ±0.5 deg (3σ). 2003 OS is targeted to 600 km circular orbit, 45 deg inclination; semi-major axis dispersions ±100 km (3σ); inclination dispersions ±1.0 deg (3σ); eccentricity less than 0.037 (3σ).					

The ΔV statistics for each maneuver are calculated based on the orbiter and OS orbit dispersions listed in the previous section and the results of a Monte Carlo simulation of the nodal phasing maneuvers. It should be noted that the ΔV for Maneuvers #2 through #5 contains a large deterministic component, which corresponds to the ΔV required to transfer from a 250 x 1400 km orbit (orbiter post-MOI orbit) to a 600 x 600 km orbit (nominal OS orbit). This deterministic ΔV (for purely in-plane maneuvers) amounts to approximately 220 m/s. Maneuvers #2 through #5 account for most of the total ΔV for the 2003 OS intermediate rendezvous. Together, these maneuvers are used to change semi-major axis at the start and end of nodal phasing and to correct semi-major axis, eccentricity, and line of apsides to nearly match those of the OS. The next largest ΔV component corresponds to the inclination correction maneuver (Maneuver #1). The Hohmann transfer maneuvers (Maneuvers #7 and #8) are very small, given the small (<10 km) semi-major axis difference prior to the transfer.

The total ΔV required for the 2003 OS intermediate rendezvous is estimated to have a mean of 266 m/s and a 1σ value of 27.5 m/s. At the 99% probability level, the required ΔV is approximately 349 m/s.

2005 OS Maneuver Summary

For the 2005 OS rendezvous, the orbiter will start from an orbit that corresponds to the orbit of the 2003 OS at completion of the 2003 OS terminal rendezvous phase. This orbit is nominally the target 2003 OS orbit, which is 600 km circular orbit at 45 deg inclination, but with the following dispersions: ±100 km (3σ) semi-major axis, ±1.0 deg (3σ) inclination, and eccentricity less than 0.037 (3σ). The 2005 OS will be in an orbit that is a 600 km circular orbit at the inclination predicted for the orbiter at completion of the 2003 OS rendezvous and at a specified node, but with the following dispersions: ±100 km (3σ) semi-major axis, ±1.0 deg (3σ) inclination, eccentricity less than 0.037 (3σ), and ±70 deg (3σ) with respect to the specified node.

On the rendezvous timeline shown in Figure 1, the intermediate rendezvous maneuver sequence for the 2005 OS begins on 11 February 2007, at completion of the 2003 OS rendezvous. The 2005 MAV will have placed the 2005 OS in orbit 18 weeks earlier on 8 October 2006. During those 18 weeks (N1), an uncontrolled nodal error has accumulated relative to the desired node on 11 February 2007. This ±70 deg (3σ) nodal error must be removed during the 13 week (N2) controlled nodal phasing period for the 2005 OS. The 2005 OS rendezvous is completed in 18 weeks on 17 June 2007. The intermediate rendezvous phase lasts for 17 weeks, of which the last four weeks after nodal phasing are used for the remaining orbit-matching maneuvers prior to the start of the terminal rendezvous phase.

The date for completion of the 2003 OS rendezvous is a parameter that can be used to minimize the total ΔV for both rendezvous. Changing the 2003 OS rendezvous completion date changes the N1/N2 combination for the 2005 OS rendezvous and the time allowed for 2003 OS nodal phasing. Moving the 2003 OS rendezvous completion date earlier will cause the 2003 OS rendezvous ΔV to increase, but the 2005 OS rendezvous ΔV will decrease because N1 will be smaller and N2 will be larger. N1 and N2 always add to 31 weeks for the assumed 2005 MAV launch date of 8 October 2006 (just before solar conjunction). The 2003 OS rendezvous completion date shown on Figure 1 is the date that minimizes the 99% probability level total ΔV for both rendezvous, given the assumptions, ground rules and constraints listed in the previous section.

Table 3 summarizes the intermediate rendezvous phase maneuvers for the 2005 OS rendezvous. The ΔV statistics for each maneuver are calculated based on the orbiter and OS orbit dispersions listed in the previous section, the N1/N2 values shown in Figure 1, and the results of a Monte Carlo simulation of the nodal phasing maneuvers. Since the orbiter starts from an orbit "relatively close" to the orbit of the OS, there is no large deterministic component for Maneuvers #2 through #5. However, these maneuvers still account for the majority of the total ΔV for the 2005 OS intermediate rendezvous. As was the case for the 2003 OS rendezvous (Table 2), the next largest ΔV component corresponds to the inclination correction maneuver (Maneuver #1), and the Hohmann transfer maneuvers (Maneuvers #7 and #8) are very small, given the small (<10 km) semi-major axis difference prior to the transfer.

Table 3

2005 OS RENDEZVOUS MANEUVER SUMMARY

	Purpose of Maneuver	**Comments (See notes at bottom of table.)**	**ΔV (m/s)**		
			Mean	**1σ**	**99%**
1	Correct inclination of orbiter to be same as that of OS.	Performed after rendezvous with 2003 OS is completed and orbit of 2005 OS is determined.	16	±12	52
2, 3	Maneuver #2 changes semi-major axis of orbiter to establish differential nodal drift rate with respect to OS. Maneuver #3 changes semi-major axis of orbiter to null differential nodal drift rate when nodes are nearly aligned.	Maneuver #2 performed a few days after Maneuver #1. Maneuver #3 performed 13 weeks later, when the line of nodes of orbiter and OS are within a few degrees of matching. (For some cases, three or more maneuvers may be required instead of just two.)	47	±31	140
4, 5	Correct a, e and ω of orbiter to be almost identical to that of OS: $\Delta a \cong 10$ km $\Delta e \cong 0$ $\Delta\omega = 0$ A small bias in a (and thus orbital period) is necessary such that the correct relative phasing will exist to allow rendezvous at Maneuver #8.	Maneuver #4 performed a few days after Maneuver #3. Maneuver #5 performed a few days after Maneuver #4. **The ΔV for these maneuvers is included in the total for Maneuvers #2 and #3.**	—	—	—
6	Correct errors in a, e, ω and i from previous maneuvers and alter the line of nodes, if necessary, to allow a co-planar relationship to exist at time Maneuver #8 (rendezvous) with correct relative phasing.	Maneuver #6 performed about one week after Maneuver #5. (Under some circumstances two or more maneuvers may be required.)	12	±7	34
7	Initiate near-Hohmann transfer to desired transition point for start of terminal rendezvous phase.	Maneuver #7 performed about two weeks after Maneuver #6.	2.5	±0.7	4.5
8	Perform final maneuver for Hohmann transfer.	Maneuver #8 performed approximately one hour (one-half orbit) after Maneuver #7.	2.5	±0.7	4.5
		2005 OS Total	80	±34	182

Orbiter initial orbit is same as 2003 OS orbit after completion of 2003 OS rendezvous.

2005 OS is targeted to 600 km circular orbit and inclination of orbiter; semi-major axis dispersions ±100 km (3σ); inclination dispersions ±1.0 deg (3σ); eccentricity less than 0.037 (3σ).

2005 MAV launch occurs just prior to solar conjunction (October 8, 2006); 2005 OS nodal drift is uncontrolled for 18 weeks (from launch through completion of 2003 OS rendezvous); 2005 OS nodal phasing occurs during 13 weeks following completion of 2003 OS rendezvous.

The total ΔV required for the 2005 OS intermediate rendezvous is estimated to have a mean of 80 m/s and a 1σ value of 34 m/s. At the 99% probability level, the required ΔV is approximately 182 m/s.

Rendezvous ΔV Summary and Success Probability

Table 4 contains a summary of the ΔV statistics for the 2003 OS intermediate rendezvous, the 2005 OS intermediate rendezvous, and the combined total ΔV for both rendezvous. The combined total ΔV

is estimated to have a mean of 346 m/s and a 1σ value of 44 m/s. At the 99% probability level, the required ΔV is approximately 478 m/s.

Table 4

INTERMEDIATE RENDEZVOUS ΔV SUMMARY

Rendezvous Case	ΔV (m/s)			
	Mean	**1σ**	**90%**	**99%**
2003 OS	266	27.5	305	349
2005 OS	80	34	128	182
2003 OS + 2005 OS	346	44	409	478

Given the results shown in Table 4, in order to achieve a 99% probability of rendezvous with both the 2003 OS and the 2005 OS, the orbiter should have a total ΔV available for intermediate rendezvous of approximately 478 m/s. If the ΔV available for intermediate rendezvous is less than this value, the probability will be less than 99%. Figure 3 shows how the probability of successfully retrieving both the 2003 OS and the 2005 OS varies as a function of the ΔV available for intermediate rendezvous. For example, the success probability decreases to 90% for an intermediate rendezvous ΔV of 409 m/s (a reduction of 69 m/s relative to the ΔV required for a 99% success probability). For a 60% success probability, the required intermediate rendezvous ΔV is 350 m/s (a reduction of 128 m/s relative to the ΔV required for a 99% success probability).

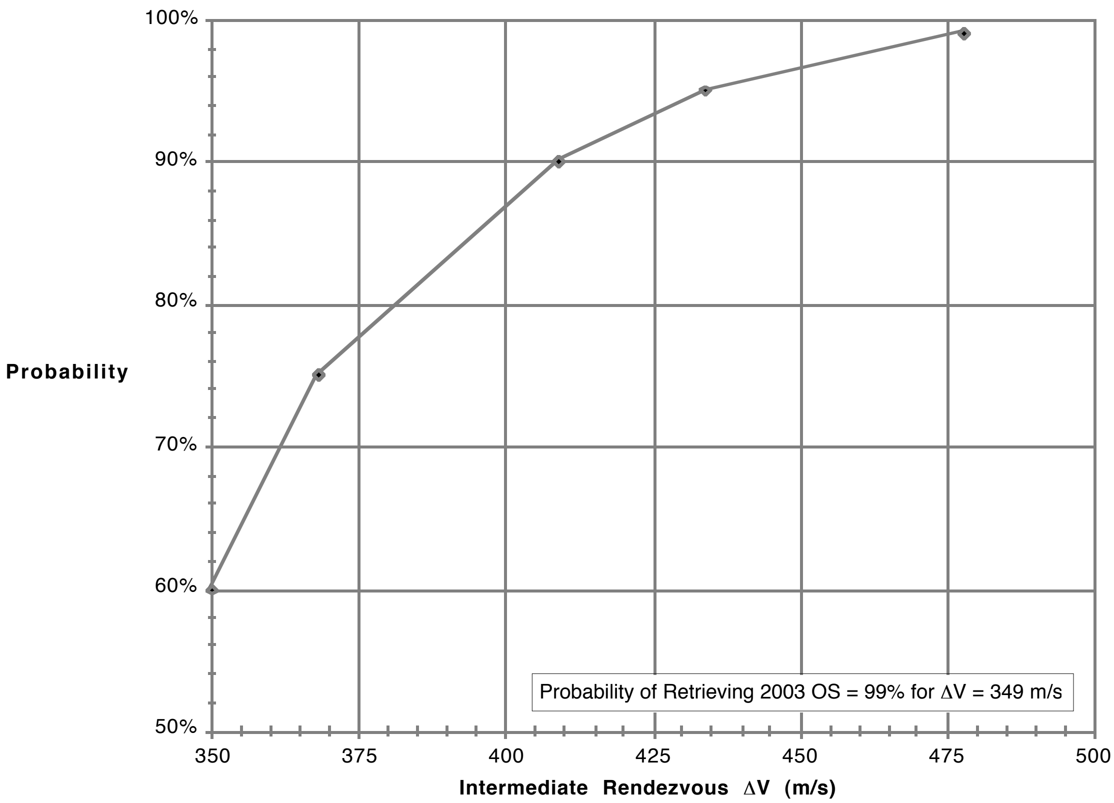

Figure 3 Probability of Retrieving 2003 OS and 2005 OS vs. Intermediate Rendezvous

Presently, the design of the orbiter is not mature enough to know exactly how much ΔV can be provided for rendezvous. By reducing the amount of propellant carried by the orbiter for propulsive maneuvers, additional mass can be allocated to offset mass growth in orbiter subsystems. A reduction (or savings) of 10 m/s in rendezvous ΔV corresponds to approximately an additional 8 kg of orbiter mass at launch. In order to maintain a 99% probability of retrieving at least one OS (an MSR Project requirement), the amount of ΔV available for intermediate rendezvous shall not be less than 349 m/s, which corresponds to the 99% probability level for the 2003 OS rendezvous. Thus, the success probability of retrieving both the 2003 OS and the 2005 OS will not be less than about 60% (Figure 3).

RENDEZVOUS TEST CASES

Two rendezvous test cases have been performed with the following objectives: (1) validate the Mars orbit rendezvous strategy, (2) confirm current estimates of the total number of maneuvers required and associated ΔV requirements, and (3) gain a better understanding of the Mars orbit rendezvous problem. One test case simulated the 2003 OS intermediate rendezvous maneuver profile, and the second test case simulated the 2005 OS intermediate rendezvous maneuver profile. The software used to perform these test cases was a modified version of the maneuver design software used for the TOPEX/Poseidon Project. The orbit propagation method used numerical integration of mean orbital elements and a Mars gravity model with 20 zonal harmonics.

Table 5

2003 OS INTERMEDIATE RENDEZVOUS TEST CASE

	Start					End*
Orbital Parameter	**Orbiter**	**OS**	**OS Error**	**OS Accuracy Req. (3σ)**	**OS – Orbiter**	**Orbiter/OS**
Periapse altitude (km)	250.0	500.0	-100.0	—	+250.0	487.6
Apoapse altitude (km)	1400.0	700.0	+100.0	—	-700.0	712.3
Semi-major axis (km)	4222.2	3997.2	0.0	±100.0	-225.0	3997.2
Eccentricity	0.136	0.025	+0.025	<0.037**	-0.111	0.028
Inclination (deg)†	45.0	46.0	+1.0	±1.0	+1.0	46.0
Ascending Node (deg)†	2.0	184.0	—	±3.0	-178.0	158.2
Argument of periapse (deg)†	4.0	184.0	—	—	+180.0	214.0
Mean anomaly (deg)	180.0	0.0	—	—	-180.0	0.0

*Total time used for rendezvous was 17.7 weeks as compared to 19.0 week allocation in the rendezvous timeline (See Figure 1).

**Worst case expected value.

†Mars-centered, Mars Mean Equator and Equinox of Date coordinate system.

Tables 5 and 6 summarize key information from these test cases. The first two columns contain the orbital elements of orbiter and the OS at the start of intermediate rendezvous. The next two columns show the errors in the orbital elements of the OS relative to the target orbit and the OS orbit accuracy requirements. The fifth column shows the differences in the orbital elements between the OS and the orbiter at the start of intermediate rendezvous. The last column shows the orbital elements at the end of intermediate rendezvous (same for orbiter and OS[4]). Both test cases were designed to be very stressful in

[4] The small differences in the orbits of the orbiter and the OS at the end of intermediate rendezvous that define the transition point for the start of the terminal rendezvous phase have been ignored in these results.

order to investigate whether the rendezvous strategy and associated maneuver profile would be able to accomplish rendezvous within the estimated ΔV requirements.

For the 2003 OS test case (Table 5), the orbiter starts from the nominal post-MOI orbit (no errors). The 2003 OS has the nominal semi-major axis, but the orbit eccentricity is significant (0.025), so that the periapse altitude is 100 km low, and the apoapse altitude is 100 km high. The OS also has a 3σ inclination error (+1.0 deg). The node and argument of periapse of the OS both differ from that of the orbiter by about 180 deg. The node of the OS is 182 deg "behind" that of the orbiter, and the OS nodal rate is higher than that of the orbiter. Nodal alignment is achieved by increasing the semi-major axis of the orbiter to slow its nodal rate, so that the OS node will "overtake" the orbiter node. The orbital elements of the orbiter/OS at the end of intermediate rendezvous are different from the starting values for the OS. The reason for this is that the non-spherical Mars gravity field harmonics (primarily J_2) cause secular changes to node and argument of periapse and periodic variations in the other orbital elements. From the note at the bottom of Table 5, the total time to complete intermediate rendezvous was 17.7 weeks as compared to the 19 week allocation. The maneuvers following nodal phasing were completed in less time than indicated in the 2003 OS maneuver profile in Table 2.

Table 6

2005 OS INTERMEDIATE RENDEZVOUS TEST CASE

	Start					End*
Orbital Parameter	**Orbiter**	**OS**	**OS Error**	**OS Accuracy Req. (3σ)**	**OS – Orbiter**	**Orbiter/OS**
Periapse altitude (km)	475.6	446.8	-153.2	—	-28.8	447.2
Apoapse altitude (km)	724.4	553.2	-46.8	—	-171.2	552.8
Semi-major axis (km)	3997.2	3897.2	-100.0	±100.0	-100.0	3897.2
Eccentricity	0.031	0.014	+0.014	<0.037**	-0.017	0.014
Inclination (deg)†	46.0	45.0	-1.0	±1.0	-1.0	45.0
Ascending Node (deg)†	80.2	1.2	-79.0	±3.0	-79.0	297.2
Argument of periapse (deg)†	279.3	238.4	—	—	-40.9	302.2
Mean anomaly (deg)	77.2	227.4	—	—	+150.2	180.0

*Total time used for rendezvous was 16.7 weeks as compared to 17.0 week allocation in the rendezvous timeline (See Figure 1).

**Worst case expected value.

†Mars-centered, Mars Mean Equator and Equinox of Date coordinate system.

For the 2005 OS test case (Table 6), the orbiter starts from the orbit of the 2003 OS at the end of the 2003 OS test case. The reason that the orbital elements in the first column of Table 6 are not identical to those in the last column of Table 5 is that the 2005 OS test case starts 13 days after completion of the 2003 OS intermediate rendezvous, during which time the orbit has been changed by Mars gravity field perturbations. The orbiter's orbit, therefore, has errors similar to those of the 2003 OS: low periapse altitude (-124 km), high apoapse altitude (+124 km), significant eccentricity (0.031), and high inclination (46 deg). The 2005 OS has a 3σ semi-major axis error (-100 km) and also a 3σ inclination error (-1.0 deg). The node of the 2005 OS differs from that of the orbiter by about 79 deg, which is actually about 10 deg larger than the maximum error than can accumulate during the 18 weeks from launch of the 2005 MAV for a 3σ semi-major axis error. The node of the orbiter is 79 deg "behind" that of the OS, but the orbiter nodal rate is lower than that of the OS. Nodal alignment is achieved by decreasing the semi-major axis of the orbiter below that of the OS to cause its nodal rate to be greater than that of the OS, so that the orbiter will "overtake" the OS. From the note at the bottom of Table 6, the total time to complete intermediate rendezvous was 16.7 weeks as compared to the 17 week allocation.

Table 7 shows the results of the 2003 OS and 2005 OS rendezvous test cases in terms of the sequence of maneuvers performed, what each maneuver accomplished, and the ΔV required for each maneuver. The total ΔV for each rendezvous and the total ΔV for the two rendezvous are given at the bottom of the table. A total of 10 maneuvers were required to accomplish intermediate rendezvous for each test case. The maneuver profile for each rendezvous is consistent with the maneuver strategies outlined in Tables 2 and 3. The total ΔV for the 2003 OS test case (321 m/s) was slightly lower than the estimated 99% ΔV requirement (349 m/s) for the 2003 OS in Table 4. For the 2005 OS test case, the total ΔV (220 m/s) is somewhat higher than the estimated 99% ΔV requirement (182 m/s) for the 2005 OS in Table 4. The ΔV totals for these test cases are high because they contain an unrealistically large number of instances of worst-case errors.

Table 7

INTERMEDIATE RENDEZVOUS TEST CASE ΔV RESULTS

Orbiter Maneuver	Purpose of Maneuver	Rendezvous	
		2003 OS Rendezvous	2005 OS Rendezvous
1	Correct inclination.	64.0	57.5
2	Change semi-major axis to establish differential nodal drift rate with respect to OS.	81.5	67.0
3	Change semi-major axis to null differential nodal drift rate when nodes are nearly aligned.	125.0	29.0
4	Partial correction of semi-major axis, eccentricity and argument of periapse.	15.0	33.0
5	Inclination trim maneuver.	1.4	0.1
6	Correct remaining differences in semi-major axis, eccentricity and argument of periapse.	17.5	16.5
7	Adjust semi-major axis to provide in-plane phasing to achieve proper relative positions of orbiter and OS for Hohmann transfer.	1.9	4.4
8	Nodal trim maneuver.	11.9	11.6
9	Maneuver to initiate near-Hohmann transfer to terminal rendezvous phase transition point.	2.4	0.5
10	Final maneuver of Hohmann transfer.	0.2	<0.1
	Total ΔV:	320.8	219.6
	Total ΔV for both rendezvous:	540.4	

The results of these two test cases achieved the intended objectives. The methodology of the Mars orbit rendezvous strategy was validated, and the total number of maneuvers required and associated ΔV requirements were consistent with estimates. In addition, a better understanding of the Mars orbit rendezvous problem was gained.

IMPROVEMENTS AND FUTURE WORK

Future work on the strategy for the intermediate phase of Mars orbit rendezvous for the MSR Mission will be concentrated in several different areas: (1) refinement of the rendezvous strategy, (2) reduction of rendezvous ΔV requirements, (3) addressing several mission trades that affect the rendezvous strategy, and (4) development of software tools to perform Monte Carlo maneuver analysis for estimation of statistical ΔV requirements and to perform rendezvous trajectory optimization (ΔV minimization) for deterministic cases.

Intermediate Rendezvous Strategy Refinements

The time allocated to search for and determine the orbit of the 2003 OS (preliminary rendezvous phase) is four weeks. Recent work to develop search scenarios indicates that this time can probably be reduced by one or two weeks. According to the timeline in Figure 1, the 2005 OS rendezvous begins immediately after the 2003 OS has been captured, and the departure orbit phasing period starts immediately after the 2005 OS has been captured. From a mission operations point of view, it would be prudent to insert some time between the completion of each rendezvous and the subsequent activity. This time could come from the reduction in the time allocated for the 2003 OS search and OD period.

The rendezvous strategy described in this paper has been developed for the timeline shown in Figure 1, which assumes the latest possible arrival date for the orbiter and a specific launch date for the 2005 MAV. These two events may actually vary in time by a considerable amount. The effects on the intermediate rendezvous strategy and ΔV requirements of considering the Mars arrival date and the 2005 MAV launch date to be statistical variables need to be determined. The expectation is that the results of such an analysis will probably result in a reduction in intermediate rendezvous ΔV requirements.

Intermediate Rendezvous ΔV Reductions

In addition to the potential ΔV reduction from considering variations in Mars arrival date and MAV launch date, there are other possible ΔV savings to be realized from changes to ground rules or changes to the intermediate rendezvous strategy. Note that all ΔV savings quoted below are for the combined total intermediate rendezvous ΔV for the 2003 OS and 2005 OS at the 99% probability level.

Post-MOI Apoapsis Altitude Dispersion. The post-MOI orbit apoapsis altitude dispersion has recently been reduced from ±250 (3σ) km to ±100 km (3σ). This results in a ΔV savings of about 5 m/s.

OS Orbit Dispersions. The results of recent MAV trajectory simulations indicate that it may be possible to reduce the OS orbit dispersions. The magnitudes of these reductions, if any, are yet to be determined. For every 10 km reduction in the OS semi-major axis uncertainty, there is about a 10 m/s ΔV savings, and for every 0.1 deg reduction in the OS inclination uncertainty, there is about a 6 m/s ΔV savings.

Variable Nodal Phasing Times. The intermediate rendezvous ΔV requirements have been generated assuming fixed nodal phasing periods: 15 weeks for the 2003 OS and 13 weeks for the 2005 OS. The nodal phasing periods have been optimized for the assumptions, ground rules, and constraints discussed earlier, which include orbit dispersions for both the 2003 OS and the 2005 OS. However, after the orbiter arrives at Mars, the orbiter RDF system will acquire the 2003 OS beacon, and the orbit of the 2003 OS will be determined. Given knowledge of the actual 2003 OS orbit, the optimal nodal phasing periods may be different. Preliminary analysis indicates that incorporating variable nodal phasing periods in the rendezvous strategy will result in a ΔV savings of approximately 30 m/s.

Inclination Correction Strategy. For some cases, it is optimal to combine the inclination correction maneuver with the first nodal phasing maneuver. The ΔV savings for this strategy has not yet been evaluated.

Mission Trades

The MAV design team has indicated that it may be possible to reduce the mass of the MAV if the MAV is targeted to a lower circular orbit or to an orbit with non-zero eccentricity. A reduction in the mass of the MAV results in a corresponding reduction in the launch mass of the lander. Lowering the OS orbit or targeting to an elliptical orbit may affect the intermediate rendezvous strategy and ΔV requirements.

A PRIORI KNOWLEDGE OF THE 2003 OS ORBIT

A key assumption in the development of the baseline strategy to accomplish rendezvous with both the 2003 OS and the 2005 is that no support is required from non-MSR flight elements to accomplish the mission. However, if non-MSR flight elements are able to locate the 2003 OS after it is launched in early 2004 and provide data from which its orbit can be determined, there are potential benefits for the Mars rendezvous strategy in several different areas. Note that all ΔV savings quoted below are for the combined total intermediate rendezvous ΔV for the 2003 OS and 2005 OS at the 99% probability level.

Early Development of Rendezvous Operations Scenarios

A priori knowledge of the 2003 OS orbit would allow for early development of a rendezvous operations strategy for retrieving both the 2003 OS and the 2005 OS. This would eliminate the need for rapid development of rendezvous scenarios immediately after the 2003 OS is detected by the orbiter during the search period that starts within a few days after MOI. In the event that non-MSR flight elements do not detect the 2003 OS within a reasonable time after launch of the MAV, and it is concluded that the OS did not achieve orbit, development of a rendezvous operations strategy for retrieval of only the 2005 OS could begin well before arrival of the 2005 orbiter at Mars.

Earlier 2005 MAV Launch

The current baseline rendezvous strategy assumes that the 2005 MAV is launched on October 8, 2006 (see Figure 1). One of the key assumptions for estimating rendezvous ΔV requirements is that launch of the 2005 MAV does not occur until after the orbit of the 2003 OS has been determined and the orbit of the orbiter at completion of the 2003 OS rendezvous has been predicted. This assumption is necessary to allow the 2005 MAV to be targeted to a specified inclination and node. The 2005 MAV may actually be ready to launch earlier than October 8, 2006 and possibly earlier than completion of the 2003 OS search. If a priori knowledge of the 2003 OS orbit is available, then the 2005 MAV can be launched when ready.

Revised MOI Targets

Given a specified inclination (nominally 45 deg) for the post-MOI orbit, there are two B-plane targets that result in two different post-MOI orbits with the specified inclination. These two orbits have different ascending node locations. This nodal difference ranges from 32 deg (for the earliest arrival date) to 61 deg (for the latest arrival date). With a priori knowledge of the 2003 OS orbit, the B-plane targets for MOI can be chosen to minimize the nodal difference between the OS and the orbiter. This approach would result in a ΔV savings that is estimated to be about 10-15 m/s.

Given a priori knowledge of the 2003 OS orbit, it would also be possible to change the orbiter's target inclination for the post-MOI orbit. The target inclination of the orbiter could be chosen to be that of the 2003 OS, instead of the nominal value of 45 deg. This strategy would result in an inclination error to be removed during the 2003 OS rendezvous of at most ±0.5 deg (3σ), which is the orbiter post-MOI inclination dispersion, instead of ±1.1 deg (3σ), which is the root-sum-square of the orbiter post-MOI inclination dispersion and the ±1.0 deg (3σ) OS inclination dispersion. The ΔV savings in this case is estimated to be about 15 m/s.

Reduced 2003 OS Search Time

Perhaps the most obvious benefit of a priori knowledge of the 2003 OS orbit is that the time allocated for detecting the OS and solving for its orbit could probably be reduced to one week. During this period, no OS search would be required; only an update to the OS orbit would be necessary. This time savings could be transferred to the intermediate rendezvous phase. The additional time for intermediate rendezvous could be used to provide more time for nodal phasing, which would reduce the ΔV required for rendezvous. Preliminary calculations indicate that the ΔV savings would be about 25 m/s.

SUMMARY AND CONCLUSIONS

The Mars Sample Return Mission will use Mars orbit rendezvous to retrieve two orbiting sample canisters containing samples of Mars surface material. The rendezvous strategy which has been developed to accomplish Mars orbit rendezvous, while satisfying mission constraints and minimizing rendezvous ΔV requirements, is divided into three phases: the preliminary rendezvous phase (OS search and orbit determination), the intermediate rendezvous phase (matching the orbits of the orbiter and the OS), and the terminal rendezvous phase (using an autonomous onboard rendezvous system to perform proximity operations and capture of the OS).

The intermediate rendezvous phase consists of a series of 8-10 maneuvers to change the orbit of the orbiter to match that of the OS. In order to significantly reduce intermediate rendezvous ΔV requirements, nodal phasing orbits are used to correct large nodal differences between the orbiter and the OS. The intermediate rendezvous phase lasts for 19 weeks for the 2003 OS and 17 weeks for the 2005 OS. The majority of the time for intermediate rendezvous is spent in nodal phasing orbits. The total ΔV required for intermediate rendezvous to retrieve both the 2003 OS and the 2005 OS is estimated to be approximately 478 m/s at the 99% probability level.

Two rendezvous test cases, with near-worst-case scenarios, have been performed to simulate the intermediate rendezvous phase for the 2003 OS and the 2005 OS using numerically integrated trajectories. These test cases have validated the rendezvous strategy and confirmed current estimates of the total number of maneuvers required and associated ΔV requirements. Future work will concentrate on refining the strategy for the intermediate rendezvous phase and reducing rendezvous ΔV requirements. Significant benefits (including a reduction in intermediate rendezvous ΔV) are possible if knowledge of the orbit of the 2003 OS can be obtained prior to arrival of the Mars Sample Return orbiter at Mars.

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